Avalanches and Scaling in Plastic Deformation

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The common perception is that materials deform by a smooth process, much like pulling taffy. Experiments and simulations have shown, however, that on a microscopic scale deformation is anything but smooth, occurring through intermittent avalanches of dislocations [1, 2]. Here we report results of recent simulations that show that the dislocations form what is called a self-organized critical system, changing the way we think about, and model, deformation.

Bak and coworkers [3] introduced the notion of self-organized criticality (SOC) to explain systems that organize themselves into a (stationary) critical state in which a minor event can start a chain reaction, leading to an effect over a large scale. The critical state is characterized by correlation functions that follow power laws. The importance of SOC theory arises from its ability to explain a wide set of diverse, and seemingly unrelated phenomena, such as earthquakes, fracture, dynamics of magnetic domains, etc. There is no rigorous definition or mathematical formalism of self-organized critical behavior; SOC is a phenomenological definition. If dislocations are self-organized critical systems, however, then we can bring to bear on deformation another important class of scaling and analysis.

We employed a two-dimensional (2-D) phase-field description of deformation to examine the deformation and avalanche behavior in a model of copper [4-5]. In the phase-field formulation, dislocations are not modeled directly; the displacement field in the slip plane serves as the order parameter in the phase field and the dislocation density is found from gradients of the displacement field. While a 2-D model, 3-D effects are included through the inclusion of obstacles to dislocation motion representing forest dislocations crossing the slip plane.

Dislocations move by bowing through the open spaces between obstacles leading to the formation of loops (see Fig. 1); under load the dislocations move and new ones form. In our simulations, as in experiment [1], we see that in each loading step, material deformation occurs in jumps separated by periods where no displacement occurs, corresponding to the release of groups, or avalanches, of dislocations. The energy released by the system is proportional to the area slipped by the dislocations, A, which reflects the size of the avalanche. Figure 2 shows the calculated loop size probability distribution at two different applied stresses. The distribution exhibits a power-law decay over a large range of sizes of the form $N(A) \sim A^{-\sigma}$, with a power law exponent $\sigma = 1.8 \pm 0.1$, in close agreement with the experimental value of about 1.6 [1]. Based on the phenomenological definition

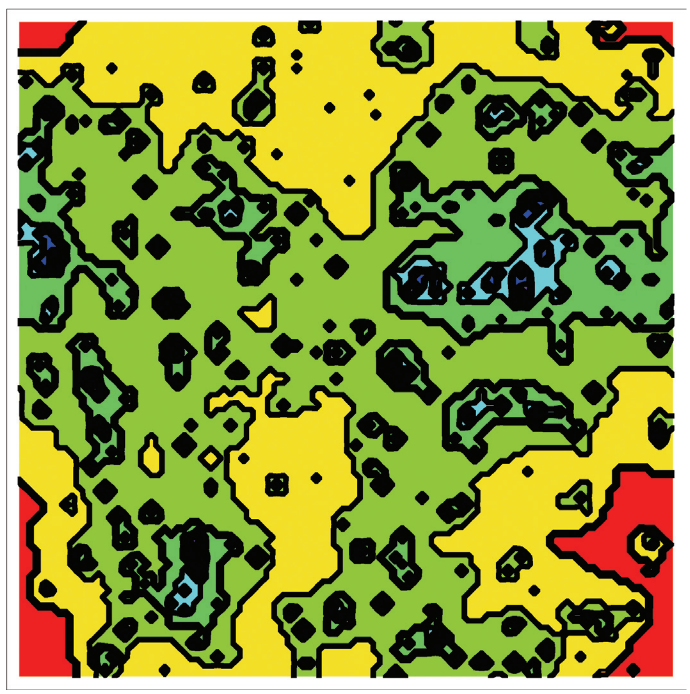

Fig. 1. ***Dislocation pattern in response to an applied stress of $\tau = 0.24 \times 10^{-4}\mu$, where μ is the shear modulus. Lines indicate contours of equal dislocation density.***

given by Bak [3], dislocations form a self-organized critical system. Dislocations thus belong to the class of nonconservative slow-driven systems characterized by scaling laws, in particular the ones used for earthquakes, fluid invasion in porous media, magnetic systems, and fracture.

In Fig. 3, we show experimental data on Ni under quasistatic load showing the shear stress and displacement as a function of time. Analysis of the displacement data yields power-law behavior with an exponent $\sigma = 1.60 \pm 0.02$, in reasonable agreement with our predicted value.

Knowing that dislocations form self-organized critical systems does nothing to help us predict the motion of individual dislocations, in the same way that knowing that earthquakes are SOC systems does not help predict when earthquakes will occur. However, knowing that dislocations form a SOC system changes our way of thinking about the problem and brings dislocations into the arena of other problems that have received a great deal of theoretical attention, suggesting that applying the framework of nonequilibrium statistical mechanics to dislocation systems is likely to be fruitful.

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[2] P. Simmonds, *Nature Mater.* **4**, 425–426 (2005).
[3] P. Bak, et al., *Phys. Rev. Lett.* **59**, 381–384 (1987).
[4] M. Koslowski, et al., *Phys. Rev. Lett.* **93**, 125502 (2004).
[5] M. Koslowski, et al., *Phys. Rev. Lett.* **93**, 265503 (2004).

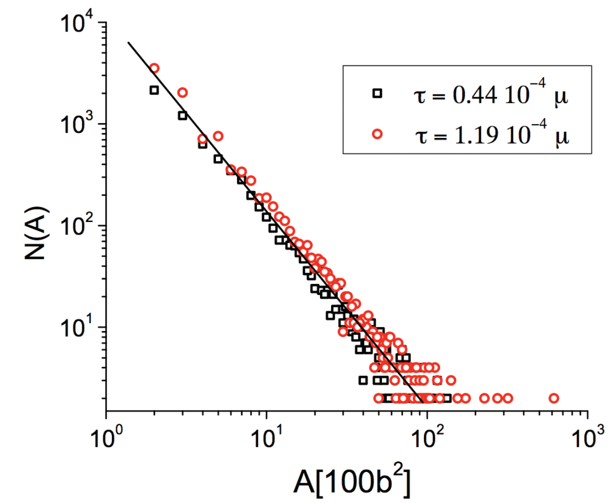

Fig. 2.
Avalanche size distribution N(A) at two applied stresses.

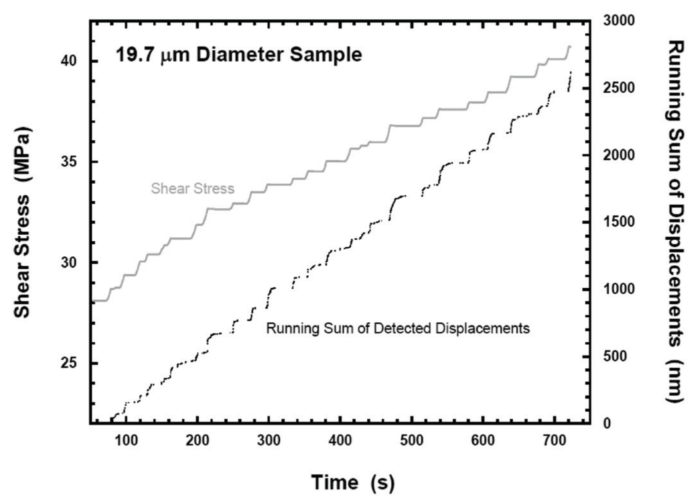

Fig. 3.
Plot of experimental shear stress and cumulative displacements as a function of time for Ni under load showing bursts of dislocations.